

On the nature of the intermittent pulsar PSR B1931+24: X-ray and optical observations

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ABSTRACT

PSR B1931+24 is a 813 ms radio pulsar which has been recently discovered to display peculiar intermittent radio emission. This source is observable in the radio band for ~ 5 –10 days and remains radio quiet for the following 25–35 days, periodically. Even more remarkable is its spin-down behaviour: the pulsar slows down at a rate a factor of ~ 1.5 faster in the radio-on than during the radio-off phase. We report here on new X-ray and optical observations of PSR B1931+24, performed with the *Chandra X-ray Observatory* and the *Isaac Newton Telescope*. Furthermore, we present here the possibility that this radio pulsar is hosted in an eccentric binary system with a very low mass companion. We then discuss our results in the intermittent isolated radio pulsar scenario and in the binary picture.

Key words: stars: pulsars: general — pulsar: individual: PSR B1931+24

1 INTRODUCTION

Very recently the study of a long term radio monitoring of PSR B1931+24 (Stokes et al. 1985; Hobbs et al. 2004), revealed a peculiar intermittent behaviour (Kramer et al. 2006). This ~ 813 ms radio pulsar is (so far) a unique system, having an active radio emission lasting between 5–10 days (radio-on phase, hereafter), and suddenly (in less than 10 s) the radio emission switches off and remains undetectable for the following 25–35 days (radio-off phase, hereafter), then it switches on again. This pattern repeats quasi-periodically, and has been monitored in several radio bands for more than 7 years (Kramer et al. 2006). Remarkably, the pulsar rotation slows down much faster (about 50%) when the pulsar is in the radio-on phase, with a frequency derivative changing from $\dot{\nu}_{\text{on}} = -(16.3 \pm 0.04) \times 10^{-15} \text{ Hz s}^{-1}$ to $\dot{\nu}_{\text{off}} = -(10.8 \pm 0.02) \times 10^{-15} \text{ Hz s}^{-1}$ across the radio-on and the radio-off phase.

From the radio timing many pulsar characteristics have

been derived; such as an estimate of the dipolar magnetic field $B \sim 2.6 \times 10^{12} \text{ G}$, a characteristic age $\tau_c \sim 1.6 \text{ Myr}$, and the pulsar dispersion measure $DM = 106.03 \pm 0.06 \text{ cm}^{-3} \text{ pc}$, which gives a rough estimate of the pulsar distance of $\sim 4.6 \text{ kpc}$ (see Tab. 1 in Kramer et al. 2006).

In §2 and §3 we report on the results of X-ray and optical observations of this system taken with the *Chandra X-ray Observatory* and the *Isaac Newton Telescope*. In §4 we present the possibility that this pulsar is hosted in a binary system with a relatively low mass companion star and in §5 we derive constraints on the orbital parameters and companion mass by fitting an orbital solution to the radio data. We then discuss the results in §6 considering both the isolated and binary pulsar possibilities.

2 X-RAY OBSERVATION

The *Chandra* Advanced CCD Imaging Spectrometer (ACIS) observed PSR B1931+24 on 2006 July 20th, for an on-source

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exposure time of $\sim 9.7 \text{ ks}^1$. The target position has been placed in the standard back-illuminated ACIS S3 aimpoint, using the FAINT mode. We correct the astrometry for any processing offset and we cleaned the image for the hot pixels.

Running the CIAO `celldetect` and `wavedetect` tools, no X-ray sources were detected in the whole ACIS-S3 CCD, especially coincident with the PSR B1931+24 accurate radio position (19:33:37.8752(31) +24:36:40.072(42); errors are at 1σ confidence level); 4 unrelated sources were instead detected in the other CCDs at $> 5\sigma$ confidence level over the background. No photons were detected in a radius of $1''$ around the target radio position. As described by Gehrels (1986), we obtained a 99% upper limit on the source count rate of $4.74 \times 10^{-4} \text{ count s}^{-1}$. Assuming an absorption value of $N_H = 8.3 \times 10^{21} \text{ cm}^{-2}$ (derived for the pulsar position from Dickey & Lockman 1990), and using the PIMMS calculator, we derived a 99% upper limit on the 0.3–10 keV unabsorbed flux of $7 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ or $1.2 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$, assuming a black body ($kT = 0.3 \text{ keV}$) or a power law ($\Gamma = 2.5$) spectral decomposition, respectively. At 4.6 kpc these fluxes translate into a 99% upper limit on the unabsorbed 0.3–10 keV X-ray luminosity of $1.7 \times 10^{31} \text{ erg s}^{-1}$ and $3 \times 10^{31} \text{ erg s}^{-1}$, depending on the assumed X-ray spectrum.

This *Chandra* X-ray observation of PSR B1931+24, kindly accorded us in the Director Discretionary Time, was aimed at detecting possible X-ray emission while the pulsar was in the radio-off phase (see below). We have monitored PSR B1931+24 nearly simultaneously from the Jodrell Bank Observatory in the radio band, in order to be confident that the source phase was the one expected. Unfortunately, the *Chandra* observation happen instead to be performed while the source was unexpectedly in the radio-on phase (see Sec. 6.2 for further details).

3 OPTICAL OBSERVATIONS

We observed the field of PSR B1931+24 with the Isaac Newton Telescope located at the Roque de Los Muchachos Observatory in La Palma, for an exposure time of 10 minutes in three optical filters: g' , r' and i' (see Fig. 1 left panel). No optical counterpart was detected within the refined radio position of the pulsar. We derived 5σ upper limits on the optical emission of PSR B1931+24 of $g' > 22.6$, $r' > 22.4$ and $i' > 22.2$ magnitudes. We inferred these optical upper limits from the magnitudes of the faintest object detected at 5σ confidence level in the same CCD where the pulsar position was laying. For the astrometry we used an $11' \times 11'$ subsection of the g' image where we found 85 stars from the USNO CCD Astrograph Catalogue (UCAC2; Zacharias et al. 2004). We obtained an astrometric solution, fitting the zero-point position, scale and position angle; we had a final rms residuals of $0''.13$ in both in RA and DEC.

We inferred the reddening in the direction of PSR B1931+24 from the N_H , which gives an $A_V = 4.64$ (Predehl & Schmitt 1995). We then converted this value into an estimate of the reddening in the filter we actually used

(Rieke & Lebofsky 1985; Schlegel et al. 1998): $A_{g'} = 4.94$, $A_{r'} = 3.68$ and $A_{i'} = 2.83$.

It is worth noting that the estimate of the N_H and the reddening that is derived from DM value gives consistent results, which is to be expected for sources rather high above the Galactic Plane as this pulsar.

Considering a distance of 4.6 kpc, we inferred upper limits on the source absolute magnitude of: $i' > 6.1$, $r' > 5.2$ and $g' > 4.35$.

From our optical upper limits on the absolute magnitudes we can derive a rough range for the companion stellar type. From $r' > 5.2$, which is the most constraining limit, we derive that the star as to have a spectral type later than G8. On the other hand, the companion star cannot be a giant since those would have been easily detected.

4 ON THE POSSIBLE BINARY NATURE OF PSR B1931+24

Kramer et al. (2006) interpreted the peculiar intermittent activity of this pulsar in terms of a quenching and a re-ignition of the radio emission, and of the transient presence of a plasma whose current flow provides an additional braking torque on the neutron star while radio-on. These authors show that the observed variations in pulsar spin-down are consistent with a simple Goldreich-Julian magnetosphere and the inferred Goldreich-Julian plasma density (Goldreich & Julian 1969). Within this interpretation, these magnetospheric conditions are sufficient to explain the change in the neutron star torque, but it is not clear what determines the ~ 30 days periodicity or what could be responsible for changing the plasma flow in the magnetosphere, in particular in this quasi-periodic fashion. In fact, the observed periodicity of the radio-on and radio-off recurrence is difficult to explain in any scenario considering an isolated pulsar, and as Kramer et al. (2006) pointed out, the short shut-off time of less than 10 seconds, rules out possible scenarios like precession of the neutron star.

All these unusual properties and the crucial hint of the change in the slow down rate during these ~ 30 days periodicity may fit in a scenario in which the pulsar is hosted in a binary system. This spin-down change might in fact imply either an additional external torque during the radio-on phase (as proposed by Kramer et al. 2006), or additional angular momentum while the neutron star is radio-off. This second possibility is considered here in the binary picture.

We define here three important PSR B1931+24 radii which will be used in the next sessions: the magnetospheric radius:

$$R_m = 2 \times 10^7 \dot{M}_{15}^{-2/7} B_9^{4/7} M_{1.4}^{-1/7} R_6^{12/7} \simeq 1.78 \times 10^9 \dot{M}_{15}^{-2/7} \text{ cm} ,$$

the corotation radius:

$$R_{\text{cor}} = 0.12 \times 10^8 M_{1.4}^{1/3} P_{10}^{2/3} \simeq 2.25 \times 10^8 \text{ cm} ,$$

and the light cylinder radius:

$$R_{\text{lc}} = 0.46 \times 10^8 P_{10} \simeq 3.74 \times 10^9 \text{ cm} .$$

We define: $B_9 = B_{\text{ns}}/10^9 \text{ G}$ is the neutron star magnetic field, P_{10} is the spin period in units of 10 ms, $\dot{M}_{15} =$

¹ for details refer to <http://asc.harvard.edu/ciao/>

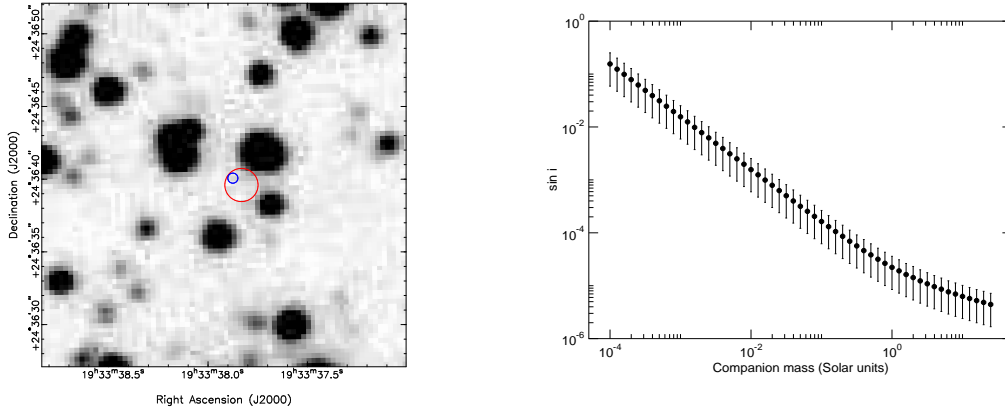


Figure 1. Left Panel: r' field of PSR B1931+24. Blue circle is the refined pulsar position (see text), while the red circle represents the old accuracy (Kramer et al. 2006; both are reported here at 95% confidence level). Right Panel: limits on the orbital inclination angle as a function of companion mass as derived from the pulsar radio timing.

$\dot{M}/10^{15} \text{ g s}^{-1}$ is the mass inflow rate toward the neutron star, and $M_{1.4} = M_{\text{ns}}/1.4M_{\odot}$ and $R_6 = R_{\text{ns}}/10^6 \text{ cm}$ are the mass and the radius of the neutron star, hereafter assumed $M_{1.4} = R_6 = 1$. Note that during the orbital motion, the only variable radius is $R_m \propto \dot{M}_{15}^{-2/7}$.

4.1 Radio pulsar is on

If the mass inflow rate from the putative companion star is very low, as it might happen at apastron of an eccentric orbit, the magnetosphere of the neutron star might be larger than the light cylinder and corotation radii: ($R_m > R_{\text{lc}} > R_{\text{cor}}$).

As a result, the centrifugal barrier is closed and incoming material from the companion star is prevented from falling towards the neutron star magnetosphere or surface, then the neutron star might behave as a radio pulsar.

The pulsar radiation pressure in this state dominates over the ram pressure of the inflowing material, preventing the matter to penetrate towards the neutron star (Illarionov & Sunyaev 1975; Davis & Pringle 1981; Stella et al. 1994; Campana et al. 1998).

This occurs when the mass inflow rate (\dot{M}) is smaller than the limiting value:

$$\dot{M}_{15, \text{radio-off}} = 5.4 \times 10^{-2} B_9^2 P_{10}^{-7/2} M_{1.4}^{-1/2} R_6^6 \simeq 0.075$$

above which the radio pulsations would quench. Hence, we expect to detect radio pulsations from the neutron star, until the accretion rate along the orbital travel is $\sim \dot{M}_{15, \text{radio-off}}$, in the PSR B1931+24 case until $\dot{M}_{15} = 0.075$. When \dot{M} becomes larger than this limit, the radio emission suddenly stops and leaves place to different regimes, where emission in other energy bands is expected (see below).

It is worth noting that when $\dot{M} \sim \dot{M}_{15, \text{radio-off}}$, the radio pulsar might not be in a stable equilibrium (Illarionov & Sunyaev 1975; Shaham & Tavani 1991); depending on the stability of the mass inflow rate (e.g. over the orbit). Actually, sporadic variability of the radio-on duration of PSR B1931+24 has been observed (Kramer et al. 2006).

4.2 Radio pulsar is off

If the mass inflow rate starts to increase, e.g. approaching periastron in an eccentric orbit, we expect a correlated decrease of the magnetospheric radius which becomes smaller than the light cylinder ($R_{\text{lc}} > R_m > R_{\text{cor}}$). This happens when the mass inflow rate towards the neutron star becomes larger than the limiting value $\dot{M}_{15, \text{radio-off}}$, then the pulsar radiation pressure is overcome by the ram pressure of the infalling material quenching the radio pulsar mechanism. Note that when the radio pulsations are quenched, the spin down behaviour of the pulsar is not driven anymore by the magnetic dipolar loss as it was before. Different regimes are then allowed at this stage. If R_m remains greater than R_{cor} , which means $\dot{M}_{15, \text{radio-off}} < \dot{M} < \dot{M}_{15, \text{acc}}$,

$$\text{with } \dot{M}_{15, \text{acc}} = 5.97 B_9^2 P_{10}^{-7/3} M_{1.4}^{-5/3} R_6^6 \simeq 1.4 \times 10^3,$$

then the magnetosphere of the neutron star still rotates in a super-Keplerian motion and the inflowing material might either accumulate outside the magnetospheric boundary or be swept away by the magnetospheric drag: this is called “propeller” regime (Pringle & Rees, 1972; Illarionov & Sunyaev 1975; Davies & Pringle 1981; Wang & Robertson 1983; Stella, White & Rosner 1986).

Given the upper limits we derived for the possible companion star (see Sec. 3), there is a very small chance that the \dot{M} , due to the wind loss of the companion, overcomes $\dot{M}_{15, \text{acc}}$. We will then consider hereafter only the possibility that the radio-off phase is driven by the propeller regime.

What happens to the pulsar spin-down during this regime is still rather controversial, and requires model dependent hydrodynamical simulations (Romanova et al. 2003). Depending on which kind of instability and shock takes place on the pulsar magnetosphere, the spin-down rate might either increase further or be reduced by the angular momentum transferred by the infalling material to the magnetosphere.

In the PSR B1931+24 case, it is clear that the infalling material should provide a certain rotational energy in order to make the pulsar slow down less efficiently during the radio-off phase, changing the spin-down of the neutron star

by $\Delta\dot{\nu} = \dot{\nu}_{\text{on}} - \dot{\nu}_{\text{off}} = -5.5 \pm 0.4 \times 10^{-15} \text{ Hz s}^{-1}$, which converted in energy corresponds to a $\Delta\dot{E} \simeq 4\pi^2 I \nu \Delta\dot{\nu} \simeq 2.66 \times 10^{30} \text{ erg s}^{-1}$.

When the infalling matter reaches the neutron star magnetosphere then the source is expected to emit in the X-ray band with minimum luminosity of:

$$L_{\text{radio-off}} = 7 \times 10^{31} B_9^2 P_{10}^{-9/2} M_{1.4}^{1/2} R_6^6 \simeq 0.12 \times 10^{31} \text{ erg s}^{-1}$$

and a maximum luminosity, in our case, related to the maximum wind loss we might expect from the inferred companion type (see also Sec. 6.2 for further constraints on the maximum X-ray luminosity). After periastron passage, the light companion star moves toward apastron, the magnetospheric boundary expands because of the decreasing mass inflow rate and the centrifugal barrier closes again and the radio pulsar mechanism can resume again.

5 LIMITS ON THE ORBITAL SOLUTION FROM THE RADIO TIMING

If the pulsar happens to be in a binary system, the motion of the pulsar about the system's centre of mass should leave a periodic signature in the remaining timing residuals. We did not see any distinctive features in the radio timing we could confidently address to an orbital motion. Using the maximum amplitude of the remaining timing residuals $\Delta t_{\text{res}} \sim 700 \mu\text{s}$, after modelling the radio data with two spin down components (Kramer et al. 2006), we could then place limits on the corresponding orbital parameters by interpreting Δt_{res} as caused by a ‘‘Roemer delay’’, i.e. the light-travel time across the orbit (e.g. Lorimer & Kramer 2005). We then set:

$$\Delta t_{\text{Roemer}} = x \left[(\cos E - e) \sin \omega + \sin E \sqrt{1 - e^2} \cos \omega \right]$$

equal to Δt_{res} . Here, E is the eccentric anomaly, e the eccentricity and ω the longitude of the periastron. Furthermore, $x = a_p \sin i / c$ is the projected semi-major axis measured in light-seconds which is a function of $a_p = a_R M_c / (M_p + M_c)$, the semi-major axis of the pulsar orbit².

On the other hand, the relative orbit a_R , the orbital period and masses are related according to Kepler's 3rd law:

$$\frac{4\pi^2}{P_{\text{orb}}^2} \left(\frac{a_R}{c} \right)^3 = T_{\odot} (M_p + M_c),$$

with the masses measured in solar masses and $T_{\odot} = GM_{\odot}/c^3 = 4.925490947 \mu\text{s}$. Assuming then $P_{\text{orb}} \sim 30 \text{ d}$ and $M_p \sim 1.4 M_{\odot}$ we can derive an estimate for the orbital inclination angle as a function of companion mass in the following way: for a given companion mass M_c we performed Monte-Carlo simulations drawing possible values for E , ω and e from uniform distributions over $[0, 2\pi]$ and $[0, 1]$, respectively. Note that the distribution for the eccentricity is not expected to be uniform (i.e. it is likely to be skewed to small eccentricities) but for our purposes this assumption is sufficient as we were mostly interested in upper bounds for the inclination angle. For each companion mass, one million

Monte-Carlo runs were performed and the median and 95% confidence limits were computed (see Fig. 1 right panel). Hence, for reasonable companion masses the tight limit on a detectable periodicity in the timing residuals implies rather small orbital inclination angles ($\leq 15^\circ$).

6 DISCUSSION

We presented here the possibility that PSR B1931+24 might hosted in a binary system with a very low mass companion (later than a G8 type), with a ~ 30 days orbital period and an orbital inclination $\leq 15^\circ$. The X-ray and optical upper limits we derived from our observations helped us to constrain this binary scenario but unfortunately cannot yet give a conclusive answer to the isolated or binary nature of PSR B1931+24; we discuss below both scenarios.

6.1 PSR B1931+24 as an intermittent isolated pulsar

As we already discussed in Sec. 4, there are a few PSR B1931+24 observational properties which are difficult to explain if the pulsar is an isolated neutron star. However, the upper limits derived here from X-ray and optical observations during the radio-on phase, are both well in agreement with the isolated scenario. In fact, an isolated radio pulsar of 1.6 Myr at a distance of 4.6 kpc, is not expected to be hot enough to produce detectable X-ray emission from its surface (Yakovlev & Pethick 2004), although there are a few cases of radio pulsars, even older than PSR B1931+24 and with similar \dot{E} , which have been detected in the X-ray band (Zavlin & Pavlov 2004).

On the other hand, the optical emission from radio pulsars is rather faint and usually undetectable even with the largest telescopes of the present generation. Only four pulsars (e.g. the Crab and Vela pulsars) have been detected with optical pulsations while for a handful of pulsars, only an optical point source has been found at the pulsar position (see Mignani et al. 2006 for a recent review).

6.2 PSR B1931+24 in an eccentric binary system

We showed here that the emission properties of PSR B1931+24 are consistent with this pulsar being in an eccentric binary with a low mass star with ~ 30 days orbital period and orbital inclination $\leq 15^\circ$. We in fact suggested that the pulsar intermittency might be due to a periodic transition between the radio pulsar regime and the propeller regime during the orbital motion.

The X-ray upper limits are consistent with the source being in the radio pulsar dominated regime (note that the source was radio-on during the observations), in fact in this regime its X-ray luminosity is expected to be lower than $L_{\text{radio-off}}$, well consistent with our upper limit.

During the radio-off phase, instead, the source would be expected to be bright in X-rays. The accretion theory predicts a minimum X-ray luminosity of $L_{\text{radio-off}}$, while the upper limit on this luminosity is constrained by the maximum wind that such a low mass companion star might produce. Taking into account this constraint, we expect the X-ray luminosity of the system in radio-off phase being between

² i is the orbital inclination angle, c is the speed of light, M_p the pulsar mass, M_c the companion mass and a_R is the size of the relative orbit.

$1.2 \times 10^{30} - 1.6 \times 10^{32} \text{ ergs}^{-1}$. Note that the short lasting X-ray emission of this system during its periastron passage, and the insufficient flux detection limit of current and past X-ray surveys and monitoring programs (e.g. ROSAT and the RXTE/ASM), does not make the non detection of any X-ray counterpart anyhow constraining. Unfortunately, our *Chandra* observation took place while the source was radio-on. This happened because of the relatively uncertain duration of both phases: the radio-on phase rarely might happen to be longer than the average duration (the \dot{M} variability timescale is rather uncertain), and the relatively large error (\sim a few days) on the putative periastron passage. From the optical upper limits, the possible companion star is expected to be a low mass star later than a G8 type, which means that the centre of mass of the system is closer to the neutron star than to the companion star: this implies that the low mass companion star is orbiting around the pulsar.

However, also this binary scenario still presents an unsolved issue. Can accretion from the low wind loss of such a small mass star be enough to switch the pulsar from the radio emitting regime to the propeller? In fact, typical wind rates for e.g. a K0 star are insufficient to produce the limiting value of $\dot{M}_{15, \text{radio-off}}$ by ~ 2 orders of magnitudes. This problem might be partially but not totally alleviated by taking into account the irradiation (Podsiadlowski 1991; D'Antona & Ergma 1993). A low mass star irradiated by the radio pulsar emission is expected to expand, even if the radiation bath is not particularly extreme, and its wind emission to increase substantially. In our case, considering a G8 to K0 star, this irradiation process cannot be dominant on the stellar wind emission because the relatively low rotational energy of PSR B1931+24 with respect to the stellar surface temperature ($L_{\text{irr}} = f \dot{E}_{\text{rot}} (R_s/2a_p)^2$, where R_s is the companion star radius). However for a much lighter star or even considering the possibility of having a gaseous planet orbiting around the pulsar, this process might have a substantial role, and might produce strong winds toward the pulsar while at periastron.

A further possibility might be to consider the companion wind as the source of the plasma appearance in the scenario proposed by Kramer et al. (2006). In fact, if the low stellar wind from the light companion star is indeed insufficient to drive the radio pulsar in the propeller regime, might be instead enough to provide the amount of plasma needed to produce the spin-down change at every periastron passage. Note that in this picture, at the periastron passage we would expect the radio-on phase, while in the propeller scenario it would had been expected at the apastron of the orbit. However, also in this picture the radio quenching still remains puzzling (as in the isolated scenario though): we in fact would expect to see the pulsar at anytime although with two different spin-down behaviours.

7 CONCLUSION

We showed that PSR B1931+24 behaviour, in particular its radio-on and radio-off periodical activity, the change in its spin-down (Kramer et al. 2006), and the X-ray, optical and radio timing limits derived here, might be explained by a low mass companion star orbiting around the pulsar with a ~ 30 days period and an orbital inclination of $\leq 15^\circ$. How-

ever, there still remains an open issue, in particular whether the companion star can provide the requested mass inflow rate. This can be figured with further multi-band observations: e.g. deep optical/IR observations to detect or constrain further the companion mass and X-ray observations during the radio-off phase. On the other hand, further theoretical efforts are needed to investigate whether a physical mechanism might be responsible of an intrinsic intermittency of PSR B1931+24 as an isolated pulsar. In any case many of these systems might be present in our and other Galaxies missed so far because of their short period of radio activity, or alternatively, some known pulsars might have not yet been recognised as intermittent.

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